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The peculiarities of the boiling process at subatmospheric pressure

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Abstract

The heat exchange peculiarities in the vacuum boiler, where boiling liquid is the heat carrier, are considered. The peculiarities of the heat exchange processes at subatmospheric pressure are revealed, the possible method of boiling processes intensification out of the boiling crises with the maximum heat transfer coefficient is considered.

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Keywords: boiling; pressure; finning; heat transfer

1. Introduction

Nowadays the boiler plants where the heat carrier boiling occurs became widely used. Similar boiler units are applied as heat sources in the various branches of industry: chemical, microbiological, food, metal and heat-power ones.

Boiler units have to meet the following requirements: low labor and material costs under operation, simple design. The example of such unit is the vacuum boiler. The peculiarity of the vacuum boiler operation is that steam generation occurs in the vacuum environment at the temperatures below 100º C. The necessary amount of water is filled in once and during the operation process it is not taken out of the boiler anywhere. The similar operation principle provides a significant reduction of the consumed resources and develops prerequisites for the considerable economic effect. The disadvantage of the vacuum boiler is heat exchange drop in vacuum volume resulting in loss of efficiency.

The subatmospheric pressure influences the heat exchange capacity with the wall. The transfer to the boiling process in low pressure areas is related to the heat exchange drop as a consequence of molecular collisions with the surface and against each other number reduction. In vacuum conditions the considerable difficulties of vapor phase

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formation at the heating surface are created, the active evaporation centers number decreases, the vapor bubble critical radius increases, the boiling process characteristics (growth velocity, departure diameter, vapor bubbles departure frequency) vary [1].

The mechanism and heat exchange capacity changes result in the boiling crises occurrence which existence have a negative impact on the heat exchange apparatus overall efficiency. One of the determining factors of boiling crises occurrence and parameters demonstrating the heat exchange process capacity is the heat transfer coefficient which decreases with the pressure lowering. The most effective intensification method is the boiling process organization in the capillary slotted channels system. The channels under consideration can be formed by the heat exchange surface forming with the use of fins system placed on the boiling heat carrier side [2, 3].

The main objective of this research is to study the heat exchange peculiarities in the boiling area at subatmospheric pressure; to propose constructive variants of the heat exchange surfaces providing higher heat exchange capacity in the heat carrier boiling area.

2. The boiling process modeling in vacuum volume

The boiling process under the natural convection in an enclosed volume at the saturated vapor various pressure is considered in the study. The transfer to convectional phenomena in low pressure areas is connected with further heat exchange drop.

The saturation temperature is defined using the Clapeyron equation modification offered by Antoine for the pressure range from 1 to 200 kPa:

$$lnp_v = A - \frac{B}{T+C} \tag{1}$$

where T is the saturation temperature, A, B, C are the constants.

The constants values are defined by the experimental data regression technique.

At the pressure above 200 kPa the saturated temperatures are defined according to the expanded formula:

$$P = exp\left(A + \frac{B}{C+T} + D\cdot T + E\cdot T^2 + F\cdot \ln(T)\right) \tag{2}$$

Where the constants *D, E* and *F* are the information values[4].

The Antoine equation demonstrates the continuous connection between such parameters as pressure and temperature.

There are different approaches of heat transfer coefficients (α) calculation at the liquid boiling. Since the liquid heat transfer coefficient depends on the operating parameters (*q, p*), therefore, the empirical dependences are applied for the practical calculations.

When calculating the pool boiling process, it is possible to apply the M. A. Miheev and I. M. Miheeva formula:

$$\alpha = \frac{3.4p^{0.18}}{1-0.0045p}q^{2/3} \tag{3}$$

or according to V. P. Isachenko, V. A. Osipov, A. S. Sukomel:

$$\alpha = 3.0\cdot q^{0.7}\cdot p^{0.15} \tag{4}$$

When the heat transfer calculating in the developed boiling zone and at the higher heat flows and pressure, it is expedient to apply the Ju. M. Lipov and Ju. M. Tret'jakov calculation dependence:

$$\alpha = 0.9\cdot 4.34\cdot q^{0.7}\left(p^{0.14} + 1.35\cdot 10^{-2}\cdot p^2\right) \tag{5}$$

where *p* is the pressure of saturated vapors, *q* is the heat flow density [5].

The heat transfer coefficients calculation issues are also considered in the papers [6].

The boiling process organization in the capillary slotted channels system have to meet the requirement for slotted clearance (b) value between the neighboring fins not to exceed the boiling liquid capillary constant value. The boiling liquid capillary constant is calculated according to the formula:

$$l_o = \sqrt{\frac{\sigma}{g\left(\rho_l - \rho_v\right)}} \tag{6}$$

where σ is the boiling liquid surface tension coefficient; g is the gravity acceleration; p_l, p_v are the densities of liquid and vapor.

The slotted clearance value should be chosen taking into account the vapor bubble critical radius which changes with the pressure lowering. The formula for the vapor bubble critical radius calculating is as follows:

$$R_{c.r.} = \frac{2\sigma T_s}{r\rho_v\left(T_w - T_s\right)} \tag{7}$$

where σ is the boiling liquid surface tension coefficient; p_v is the vapor density; r is the vaporization heat; T_w is the wall temperature; T_s is the saturation temperature[1].

3. Methods

The boiler heat calculation is carried out by the zone method. Heat exchange in vacuum is defined by means of the balance method taking into consideration the heat transfer coefficients at boiling and condensation. The effectiveness criterion is the vacuum boiler gross efficiency.

The boiling process modelling in vacuum volume is conducted in the capillary slotted channels system (Fig. 1). The slotted channels are formed by the smooth surface (W) supply with the fining system (F). The main purpose is to provide the optimal geometrical parameters of the fins surface. These include: the fin height (H), the fin thickness (a), the slotted clearance between fins (b).

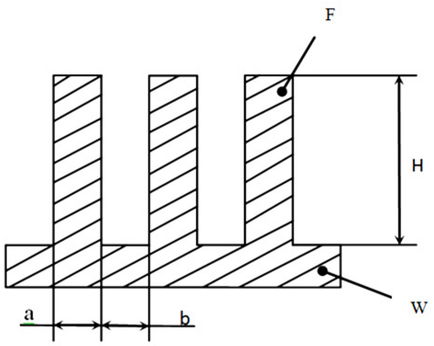

Fig. 1. The calculation model of the finned surface.

The pressure range under study is from 10 to 608 kPa. The calculations were made at the fin constant height and thickness. The slotted clearance value between fins was defined by the pressure.

4. Results and discussion

The heat transfer coefficient calculation according to three different techniques confirmed the subatmospheric pressure influence upon the heat exchange capacity in the vacuum volume upon that in the case of the pressure lowering the heat transfer coefficient is reduced (Fig. 2). The boiling process intensity decreasing in the vacuum volume results in the vacuum boiler efficiency reduction within the range of 5 % [5].

The major objective is the selection of the finning geometrical characteristics so as to provide the maximum effect. It is necessary to take into account the value variation dynamics of the boiling liquid capillary constant and vapor bubble critical radius within the different pressure range (Fig. 3, 4). With the pressure lowering the capillary constant and vapor bubble critical radius increase as a result of the liquid and vapor densities decreasing.

The computation data analysis of two parameters (boiling liquid capillary constant and vapor bubble critical radius) made it possible to define the pressure range where the given intensification method is effective (Fig. 4). The pressures operating range is limited by the pressure of 60 kPa. Under the further pressure lowering the vapor bubble critical radius starts exceeding the boiling liquid capillary constant value, within the range from 10 to 60 kPa the given method effectiveness reduces as there is a possibility of entering the unstable boiling conditions. The application of finning on the boiling heat carrier side increases the heat transfer coefficient (Fig. 5).

With the purpose of the finning realization condition determining for the boiling efficiency to attain its maximum in the low pressure area, the finning coefficient concept is introduced. In addition the boiler maximum efficiency should be achieved provided the outlet gases temperature is within the specified range from 120 to 170^{o} C.

The calculation was made at the pressure from 10 to 101 kPa within the finning coefficient range (δ) from 1.10 to 1.15. The lower limit of the finning coefficient (δ = 1.10) results from the fact that the finning coefficient application of lower values has an insufficient impact on the boiler efficiency increase, the outlet gases temperature exceeds the limit of 170^{o} C, heat losses with outlet gases are high.

The upper limit of the finning coefficient (δ = 1.15) was chosen taking into account that the further finning coefficient increasing results in the outlet gases temperature decreasing, the risks of low temperature corrosion arise.

With the finning coefficient increasing, the vacuum boiler efficient operation areas corresponding to the efficiency maximum value (Fig. 6) decrease. The fire-tube boiler efficient operation largest area having the maximum gross efficiency within the pressure range from 30 to 101 kPa is observed at the finning coefficients (δ) from 1.1 to 1.11, while the smallest area is observed at the finning coefficient (δ) of 1.15 and pressure of 30 kPa.

The maximum vacuum boiler efficiency growth is within the limits of 2 % at the pressure of 60.8 kPa having the finning coefficient (δ) of 1.13 in comparison with the analogue without finning.

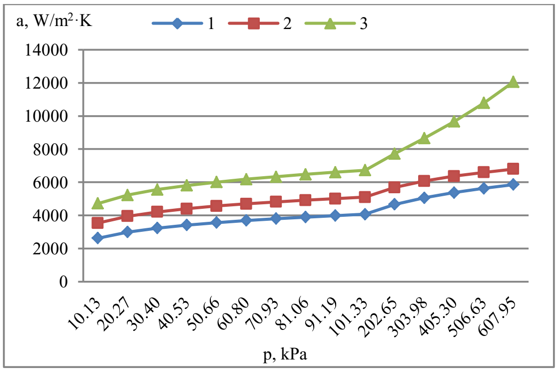

Fig. 2. The heat transfer coefficients dependences on the saturated vapors pressure under the liquid boiling: 1 – M.A. Miheev, I.M. Miheeva; 2 - V.P. Isachenko,V. A. Osipov, A. S. Sukomel; 3 - Ju.M. Lipov, Ju.M. Tret'jakov.

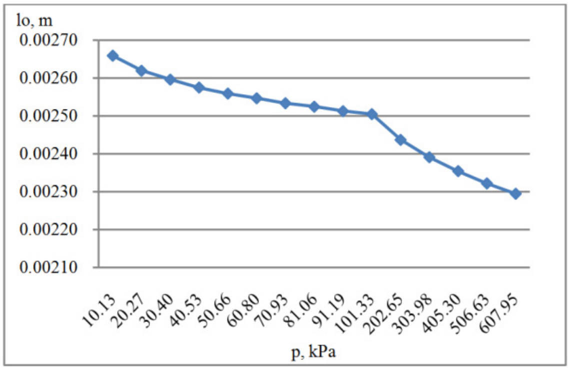

Fig. 3. The pressure impact on the boiling liquid capillar constant value.

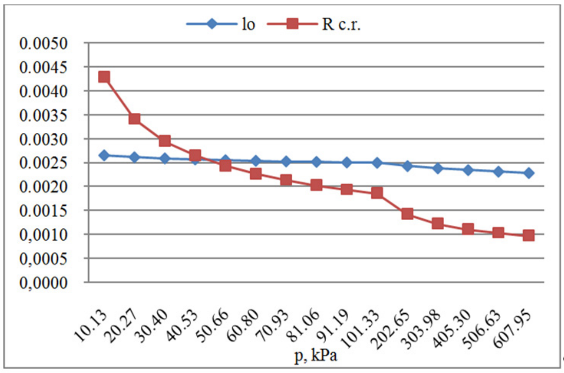

Fig.4. The calculated dependences for the bubble liquid boiling.

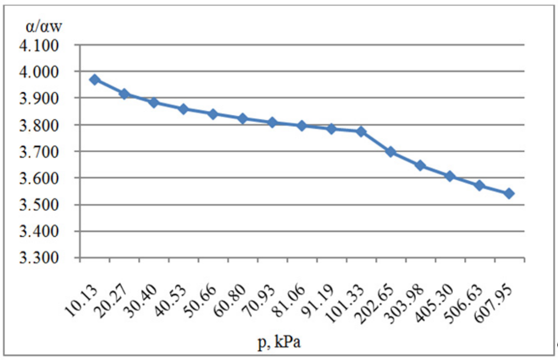

Fig. 5. The pressure impact on the finning relative efficiency.

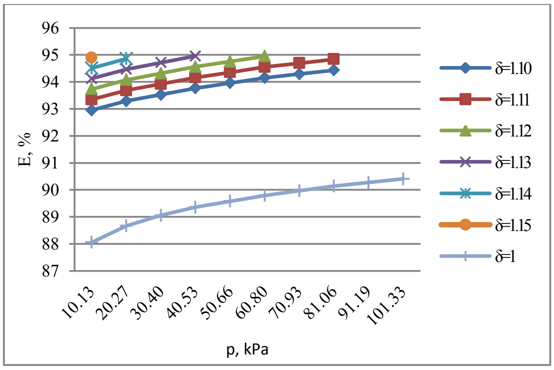

Fig.6. The pressure range of the vacuum boiler efficient operation.

5. Conclusion

It was shown that the pressure reducing in the boiling heat carrier area results in the heat transfer intensity decreasing, the intensifiers using is necessary.

It is possible to use finning as intensifiers in the form of capillary slotted channels system on condition that the slotted clearance value between fins does not exceed the boiling liquid capillary constant value. The maximum effect is achieved at the pressure of 60 kPa and finning coefficient (δ) of 1.13, the vacuum boiler efficiency growth amounts to 2%. The pressure range and finning coefficient values do not exceed the acceptable limits of the outlet gases temperature from 120 to 170 ^{o} C.

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